Improvement of synthetic aperture sonar with multi-channel projector

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***Abstract*— A synthetic aperture sonar gathers echoes from large area of seafloor per a ping, therefore the sonar needs wider width of the beam than Side scan sonar. But if the elements of the projector is just one element, it have to be small to widen the beam, and must be low sensitivity. One solutions to raise the sensitivity of the sonar is to use array as a receiver. The array is not only necessary for high sensitivity, but also the motion compensation and higher mapping rate in synthetic aperture process. Many synthetic aperture sonar are now constructed with a single transmitter with an arrayed receiver. But the projector remains small and single in many synthetic aperture sonars. The maximum detection range of synthetic aperture sonar was no longer than side scan sonar at same sonic frequency yet. To extend the sonar range, we proposed multi-channel projector whose elements lined vertically. We consider that the intensity of the projection beam increases keeping its width, by controlling a timing of the projection from each element. In addition, if the projector can receive echoes, 3D-maps can be generated simultaneously like a multi-beam echo sounder. This means synthesizing aperture process become more precise with the correct altitudes. In June 2014, we carried out survey with the synthetic aperture sonar totally for 40 hours over 5 days at off-Sanriku near border of Miyagi and Iwate prefecture. We evaluated the projector performance through detections of many artificial objects such as underwater reefs and sunken ship in the survey. We confirmed that projection beam was widen keeping projection power and maximum detection range was over 400 m in slant range. In addition, bottom detection process which is before step of 3D-mapping became easy.**

Keywords—synthetic aperture; sonar; beam forming; google earth

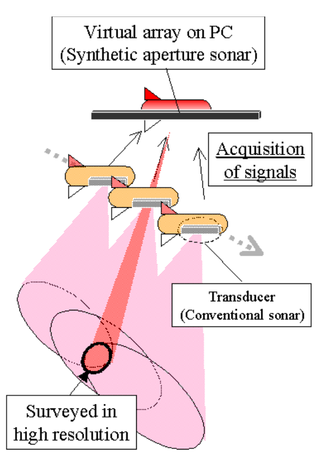

Fig. 1. Principle of synthesizing aperture

I. INTRODUCTION

A. Sonar and synthetic aperture technique

A side scan sonar (SSS) projects sonic waves to its side, and receives the echo from objects in the direction. Maximum along-track resolution, or an azimuth resolution, of the sonar is limited to the pulse interval and the pulse width. Moreover, along-track resolution deteriorates and its noise increases in proportion to the distance from the sonar device to the objects.

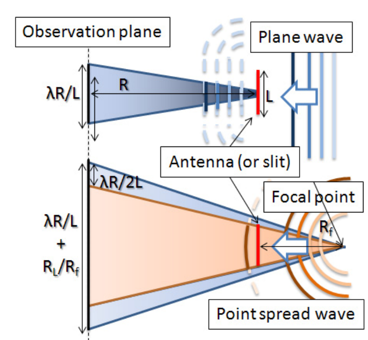

Fig. 2. Beam forming which duplicates a point spread wave

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One solution to this complex problem is to use a synthetic aperture technique. A sonar using the technique which is called synthetic aperture sonar (SAS) must go in straight lines, projecting sonic pulses and receiving echoes reflected by objects. The information in those echoes is fed into a computer, and correlated with reference signals. Then, a sonar with large transducer array is generated virtually (shown in Fig. 1). SAS achieves the same resolution in long-range detection as in short-range, and the device itself is no larger or heavier than SSS.

A development of synthetic aperture sonar was begun in late 1960s[1]. Many techniques in synthetic aperture radar (SAR) were applied to a sonar system at the first step of the development. Many problems were existed, but many were solved too. Cutrona published benchmark papers highlighting the need for an along-track array of hydrophones to increase mapping rate[2]. Many SAS are now constructed with single transmitter with an array receiver[3]. This structure is useful for not only the mapping rate, but also motion compensation of the platform. Motion of the hydrophone array was able to be estimated from the many correlations of pairs of hydrophone elements from succeeding pulses[4,5]. The array is also improved in the sensitivity of the receiver. In addition, Interferometric SAS (InSAS) with pair of vertically displaced hydrophone arrays that generates 3-D terrain map[6,7], are tried. Now, Some commercial SAS, such as HISAS-1030[8], PROSAS-Bluefin-12[9] and Shadows[10] are released commercially.

B. *Motivation*

A projector of a SAS remains small, single and low projection power yet. Multiple transmitters[11] and multiple elevation beams[12] had been proposed, but those were not effective. Therefore the maximum detection range of SAS is shorter than SSS at same sonic frequency. Long range SAS by PROSAS is Max. 350 m detection range in spite of low frequency around 60 kHz[13], and HI-SAS1030 generated excellent sonar imaged but the range of the many images were at around 150 m[14].

To extend a maximum range of SAS over 400 m, we proposed multi-channel projector whose elements lined vertically. We applied the multi-channel projector to a new our SAS. We consider that the projector, which is controlling its projection timing of the each element, increase the intensity of the beam keeping its width. In addition, if the projector received echoes, multi-beam for 3D-mapping are formed. This is very useful to calculate multi point altitudes around sonar that is needed for more precise synthesizing.

II. Synthetic Aperture Sonar with Multi-channel Projector

A. *Wider beam by a beam forming*

A wave projected from L length antenna is equal to a diffraction wave going through a L length slit[15]. At an observation plane where is enough to satisfy Far-field approximation, the beam pattern is:

$$P = |sinc(kLx/2R)| \tag{1}$$

Where P is absolute amplitude of the wave at the observation plane, k is wave number, R is range from antenna to the observation plane and x is length from center at the observation plane. Because eq. (1) includes non-linear function 'sinc', beam width is sometimes approximated to:

$$W = \lambda R/L \tag{2}$$

Where W is half length between 0 amplitude at the observation plane, λ is a wave length. The eq. (2) shows that wide beam needs short antenna which project low amplitude wave relatively.

If the wave isn't plane wave, the beam width isn't limited by eq. (2). If the waves from the part of the antenna are controlled to a point spread wave like a fig. 2, the beam will become wide. An accurate beam width can only be derived from computer simulation and will be studied on my future work. Now we suppose the beam width is:

$$Ws = \lambda R/L + (R+ R_f)L/R_f \tag{3}$$

Eq. (3) means that the beam width Ws are summation of beam width by point spread effect and W. If we project the waves at a same time, eq. (3) is equal to eq. (2).

B. *Development history of SAS in JAMSTEC*

JAMSTEC developed a SAS for over 15 years. The leftmost photo in fig. 3 is the first SAS in JAMSTEC which was on a gantry type of X-Y stage over an acoustic test tank. This was made for basic study of SAS in 2002[16]. Based on the tank test, SAS#2, Second image from the left in fig. 3, was constructed. The #2 is shallow tow-fish of neutral buoyancy.

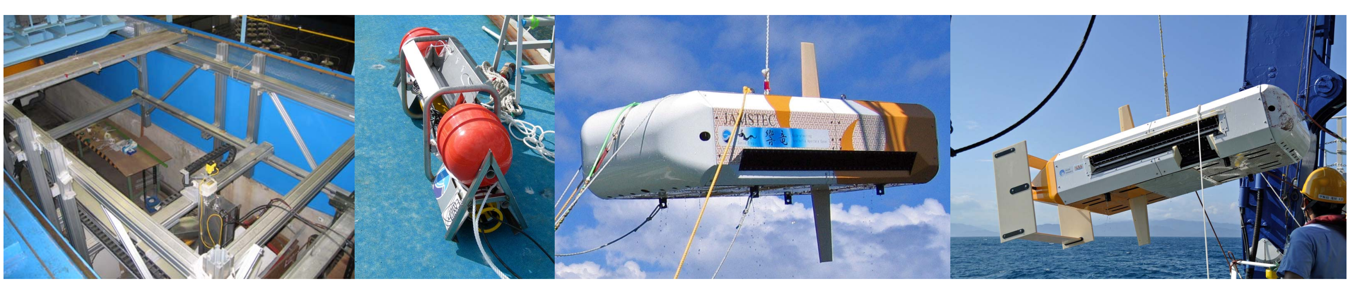

Fig. 3. SAS #1, 2 ,3 and 4 (are placed from left).

Sea trial was done with the tow-fish at Katagami bay in Nagasaki pref. in 2006[17]. Targets on the sea-bottom was observed, and the resolutions of the sonar image were improved after synthesizing process. To evaluate a performance of long-range SAS in practical usage, The SAS#3, the third image from the left in fig. 3, was constructed. This was tested in Sagami gulf in 2009. Geological characteristics were shown on the SAS image clearly in spite of rocking tow-fish near sea surface[18]. The #3 was also loaded on AUV and caught sunken submarine at 1300 m depth[19], and surveyed Kagoshima gulf and captured many hydrothermal vents in 2011[20].

SAS#4, the rightmost image in fig. 3, which has a multi-channel projector was constructed to survey large seafloor in detail. The multi-channel can be utilized for changing a directivity of projection beam. We equipped independent power-amplifier for each element. The projector has 4 rectangular elements, but space between each element are tight. This structure resembles a multi-beam echo sounder (MBES) rather than an interferometric sonar. Signal processing also resemble in MBES. The projector can work as a receiver, this resembles in an interferometric sonar. We called the SAS#4 'Syoumei'. Specification of the system is shown in Table I.

TABLE I. SPECIFICATION OF THE SAS#4 'SYOUMEI'

Synthetic Aperture Sonar #4	
Operating depth	Max. 3000 m
Weight	60 kg without tow-fish
Wave frequency	101.5-106.5 kHz
Pulse width	10 msec
Receiver	8 ch, 70 deg. vertical directivity, 0.6 deg. horizontal directivity, over -178 dB for 100-120 kHz in each elements
Projector	4 ch, 35-70 deg. vertical directivity, 5 deg. horizontal directivity
Resolutions	Max. 0.14 m in both of range and azimuth
Range	Over 375 m without synthesizing process
Neutral buoyancy tow-fish	
Weight	250 kg in air
Tow speed	3 kt @ cruising, Max.5 kt
On-board processor	
OS	Windows server 2008
Programming language	Matlab with parallel computing toolbox and C#

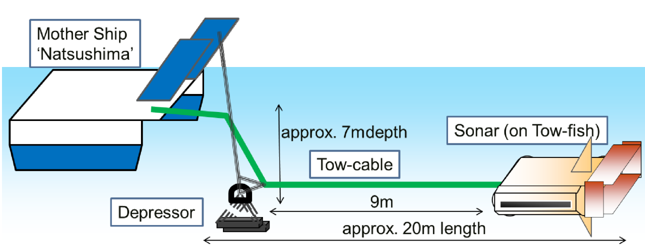

Fig. 4. Diagram of SAS loaded on a tow-fish towed by mother ship.

C. *Image processing steps*

The survey with the SAS system is done through 3 steps. After launched the SAS on the tow-fish, we turn on the SAS, and mother ship run up to planned speed to prepare the survey. When we checked the sonar pinging, we do step1: SSS images shown on on-board controller are checked, and we confirm the SAS records the echoes correctly. These are just a health check. After the survey and retrieving the SAS, we copy all recorded data to the on-board processing computer for step 2: Binary data which includes SSS images and the SAS position is converted to Keyhole Markup Language (KML) format. The KML data is imported into and displayed on Google Earth. We can check all seafloor image maps. If we find remarkable objects on the maps, we do final and important step 3: Synthesizing aperture process around the remarkable objects are done. High resolution and contrast images are generated. The high quality image can be converted and placed on the same Google Earth.

III. RESULTS AND DISCUSSIONS

A. *Research survey by Tohoku Marine Science*

The earthquake and tsunami of the Great East Japan Earthquake caused drastic changes to the marine ecosystems. It is necessary to investigate marine ecosystems to reconstruct fishery grounds. Especially, off-Sanriku was damaged hard by tsunami. It is thought that much debris was left on sea bottom at the area yet. If the position of debris is unknown, it causes many problems when the fishery boats tow net around debris. In addition, there is possibility that underwater reefs were moved by the earthquake and the tsunami. Aiming to provide scientific findings and information that contribute to determine the fishery grounds, to estimate the existing marine resources, and to confirm all the position of underwater objects again, we survey off-Sanriku with the SAS which is high performance and can find unknown object clearly. In the important survey, we had chance to evaluate the projector.

In June 2014, we carried out survey with the SAS#4 totally for 40 hours over 5 days near border of Miyagi and Iwate prefecture[21]. Depth at the area is from 100 to 250 m, but the area is gently undulated and has easy slope. The SAS#4 on the tow-fish was towed by mother ship 'Natsushima'. The towing speed was around 2 kt and towing depth was around 7 m controlled by means of changing depth of the depressor attached at a middle of tow-cable. Fig. 4 is a schematic diagram of the towing. We made mosaic map on the Google Earth for many people so as to read the map around the damaged area without expensive software. Fig. 5 is the mosaic map generated with the SAS#4. We can see many underwater reefs and unknown objects in the map. Different underwater reefs are shown in colorful frame from No. 1 to 4 on the map. And a large object, which is considered as sunken ship, was detected at an icon No. 5. We believed that this map help many people including fishers around off-Sanriku.

B. *Wider beam formed by delayed projection*

We try to widen a vertical directivity of the projector by means of controlling projection timing on each element. The projector has independent 4 elements whose width of the up

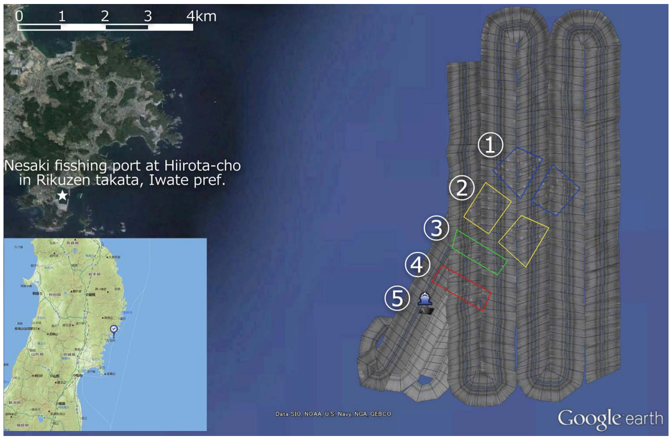

Fig. 6. Mosaic map

and down direction is approximately 9.1 mm, and width of along-track direction is approximately 69 mm. Those are stacked in the projector case with minimum space, and width of the up and down direction is approximately 37 mm totally. Wave frequency of the sonar is approximately 100 kHz.

When the projection timing is the same, the beam width at 100m range derived from eq. (2) is: (1500/100000)*100/0.037 ≈ 40.5 [m]. the width is $\tan^{-1}(40.5/2/100)*2 \approx 22.8$ [deg] in theory. When the projections from 2 outside elements are delayed, the equivalent point spread wave and the focal point are shown in fig. 6. The early wave projected from 2 inside elements go distance b, the 2 outside elements begin to project delayed wave. Because a = b + c must be satisfied by Huygens–Fresnel principle in this condition, $a = sqrt((3/2*L_e)^2 + R_f^2)$ and $c = sqrt((1/2*L_e)^2 + R_f^2)$. Thus:

$$b = sqrt((3/2*L_e)^2 + R_f^2) - sqrt((1/2*L_e)^2 + R_f^2) \qquad (4)$$

where Le is distance between each element. Then we try 4 projection patterns. The delay of the 2 outside elements was set to 0.0 1.1, 1.6 and 2.0 µsec. The beam width estimated from eq. (3) and (4) are 23, 54, 68 and 79 deg. respectively, when sound velocity is 1500 m/s.

Fig. 7 shows sonar images at the every delayed projection. No. 1, No. 2, No. 3 and No. 4 image are 0.0, 1.1, 1.6 and 2.0 µsec delay respectively. These images were generated through SSS process. Upper side of the images are by the left side projector and receiver, and lowers are by right side. Unit of horizontal axis is ping number, and vertical axis is time from each pinging. The range 0 – 150 msec in the each image are water column. The range over 150m sec are echoes from

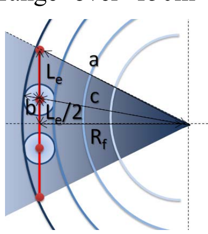

Fig. 8. Distance to focal point of equivalent point spread wave.

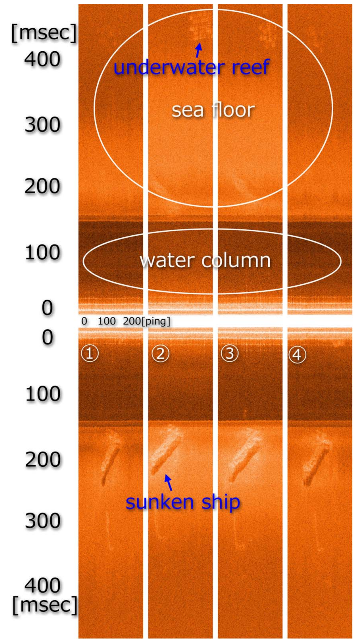

Fig. 5. SSS images in different projection beam width.

seafloor. No. 2 and No. 3 images, that are 1.1 and 1.6 µsec delay respectively, are brighter than the others at the seafloor. The bright means the sonar received high intensity of sonic wave, or high power sonic waves were projected. The delayed projection was done effectively. But No. 4 didn't become bright, besides No. 3 is darker than No. 2. These results suggested that too much delay lead projection power low. We think it is due to a phase matching error on the matching layer and the elements. The layer is effective in plane wave. The delayed projection cause non-uniformity in the layer and destructed the wave.

Then the sunken ship, which also appeared in fig. 5 at the 5 mark, was synthesized at the 1.6 µsec delayed projection. Fig. 8 is sonar images of the ship before and after synthesizing. The depth and the horizontal range are approximately 100 m. We

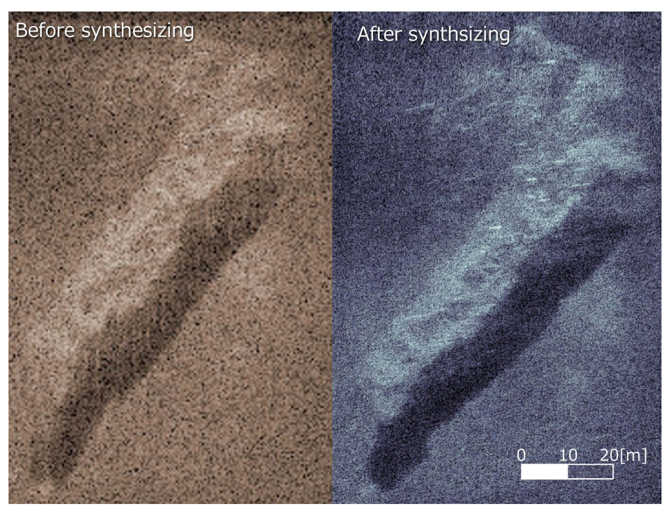

Fig. 7. (left) SSS and (right) SAS image of a sunken ship.

can see the resolution is improved, and the shadow became dark. Large reflections like clouds and small reflections like stars appeared at the upper side of the image. These proved to be fishery nets and buoys in post-project survey with ROV. These facts support that the delayed projection didn't influence to a synthesizing process.

C. Bottom detection by Multi-Beam process

Wave information are summed taking into account of the position of the target and sonar through a synthesizing process. It means that SAS needs three-dimensional position of the targets, and the position error deteriorates the image directly. We try to measure a depth of seafloor with the multi-channel projector. The projector enables beam-forming at receiving and MBES process. The left image in fig. 9 shows SSS images when the receiving beam is in the direction to face of projector, and the right is in the direction just under the sonar. A median filter is applied to the right image for noise reduction. White lines appeared in the middle of the each images mean boundary of water column and sea floor. The boundary is clearer in the right image than the left image, and the bottom detection became easy by the left image, or by the controlling of receiving beam. We have constructed a detection algorithm of just only under sonar now, but the algorithm will be updated to detect multi depth of sea floor.

D. Image resolution by synthesizing aperture

The horizontal directivity of the receiver array of the SAS #4 is approximately 0.6 deg. at -3dB attenuation standard. The along-track resolution at 100 m slant range is tan(0.6/2)*2*100 $\approx$ 1.1 [m] without synthesizing. The horizontal directivity of the each element is approximately 5 deg. and the resolution is tan(5/2)*2*100 $\approx$ 8.7 [m]. If the SAS synthesize a sonar image when the sonar is no rocking, the along-track resolution will become 8.7/1.1 $\approx$ 7.9 times as good as SSS, and results in 1.1/7.9 $\approx$ 0.14 [m]. The resolution is 3.1 m at 300 m without synthesizing process, and 0.14 m with synthesizing process theoretically.

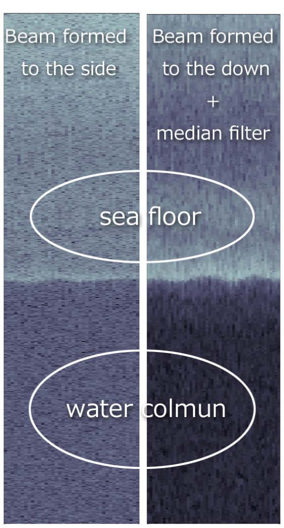

Fig. 10. SSS images in different directivity of receiving beam.

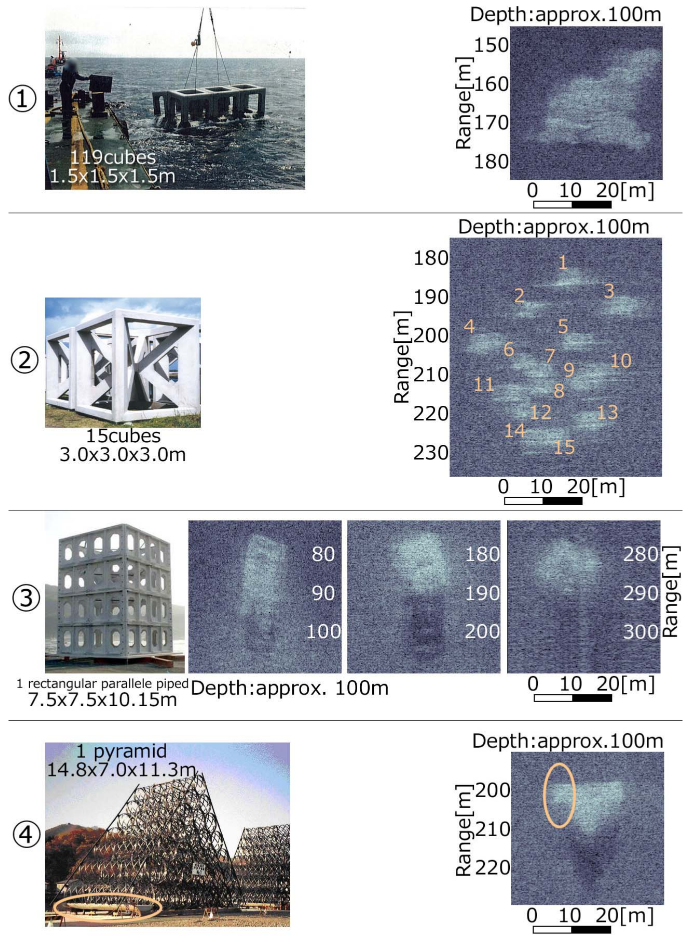

Fig. 9. 4 type of underwater reefs and its SAS images.

We estimated the SAS performance in the comparison of the sonar images before and after synthesizing. Areas from No. 1 to number 4 in fig. 8 are around 100 m depth. Different shapes of reefs had been deployed by fishery corporative at these areas. The same shape of the reefs were enclosed with the same color in fig. 5. Fig. 10 shows the underwater reefs and its SAS images. The numbers are corresponded to the numbers in fig. 5. 119 reefs, that were cubes with 1.5 m each side, appeared at the No. 1 area, but one large and undulated rock was detected in the sonar image. The cubes were consist of around 30 cm thick of frame made with concrete, therefore the along-track resolution in the sonar image was over 30 cm. 15 reefs, that were cubes with 3.0 m each side, appeared at the No. 2 area. The reefs looked like rectangular and we were able to count the number of reefs in the image. This meant that the along-track resolution was under 3 m. 1 underwater reef, that was a rectangular parallelepiped with 7.5 m each side of bottom and 10 m height, appeared at the No. 3 area. The reef had many holes on the wall, and had no roof. Fortunately, we detected same type of the reef at 90 m, 190 m and 290 m horizontal range in the same survey line. The reef at 90 m was clear and its frame was also distinguished. The hole on the wall was shown in its shadow clearly. The estimated along-track resolution in the image was less than 1 m. The hole on the reef at 190 m was barely distinguished, and the image at 290m was unclear. In these results, the along-track resolution of the synthesized sonar image deteriorated in proportion to the target range. We tried to extend a synthetic aperture length over 5 m, but the along-track resolution wasn't improved, but contrast was improved in this whole SAS survey. We guess the results were caused by precision of inertial measurement unit (IMU) equipped in the SAS. The precision of angle measurement is approximately +-0.3 deg. in roll and pitch, but +-5 deg. in bearing. The angle error leads large position error of target, especially in far range. Thus, the deterioration were marked at the far range. The along-track resolution is approximately 3.1m at 300m range if the precision of angle is +-0.3 deg. theoretically. This value is reasonable.

1 underwater reef, which was a triangle with 15 m width, 7 m depth and 11 m height, was at No. 4 area. The reef was consisted of circles made with thin fiber reinforced plastic (FRP). Weights were found at the both foot of the reed in the photo. The weights was inside of the triangle, but it look outside in the sonar image. Sonic waves are easy to go through a FRP, and wasn't reflected. But the shadow of the reef was sharper than the reflection. These suggested that the sonic waves are scattered by the FRP reefs. When we detects an object which has low reflection and low transparency of sonic wave, or a large object consisted with thin structure which is under the resolution, the its shadow is helpful to distinguish what it is.

IV. Conclusions and Future Works

We tried a multi-channel projector for SAS to widen a projection beam vertically controlling each projection timing and to detect depth of seafloor through multi-beam process on receiving beam. The effect of the projector was evaluated on resolution of sonar image. We have confirmed below:

- Projection beam is able to been widen keeping projection power by means of delayed projection with the multi-channel projector.
- The multi-channel projector is able to detect bottom just under the sonar by means of multi-beam process on receiving beam.
- An angle precision of IMU affects along-track resolution of SAS strongly.

We will try to get altitude of all range through multi-beam process with the projector. And an IMU with higher angle precision will be used. In addition, a DVL will be tried to acquire the ground velocity. These are necessary to bring out the original performance of SAS.

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